STUDIES OF THE SOLAR AND TERRESTRIAL RADIATION FLUXES OVER ARCTIC PACK ICE

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FORWARD

This is Technical Report No. 1 covering the period June 1, 1971 through December 31, 1971 on Contract No. N00014-71-A-0364-0001.

This technical report has been reviewed and is approved.

SUMMARY

ARPA-sponsored research by the University of Alaska into the solar-terrestrial radiation matrix in the Arctic Basin commenced during the spring of 1971. Surface and airborne observations continue to be carried out at Barrow, ice island T-3 and elsewhere. At the time of writing this preliminary technical report, six months after the project commenced, field work and analysis have provided some results and have indicated directions in which continued research efforts would be rewarding. These specific studies aim to aid in the understanding of the radiation phenomenon in the Arctic atmosphere and at the terrestrial Arctic surface and ultimately relate to considerations of the heat budget of the polar regions and to climate modifications and controls in that region. Relevant specific fields of study, both completed and still to be completed in the remainder of the contract period, are summarized below and are subsequently treated sequentially in the main section of this report. These are studies that are based largely on the recommendations made by the National Academy of Sciences (NAS, 1970).

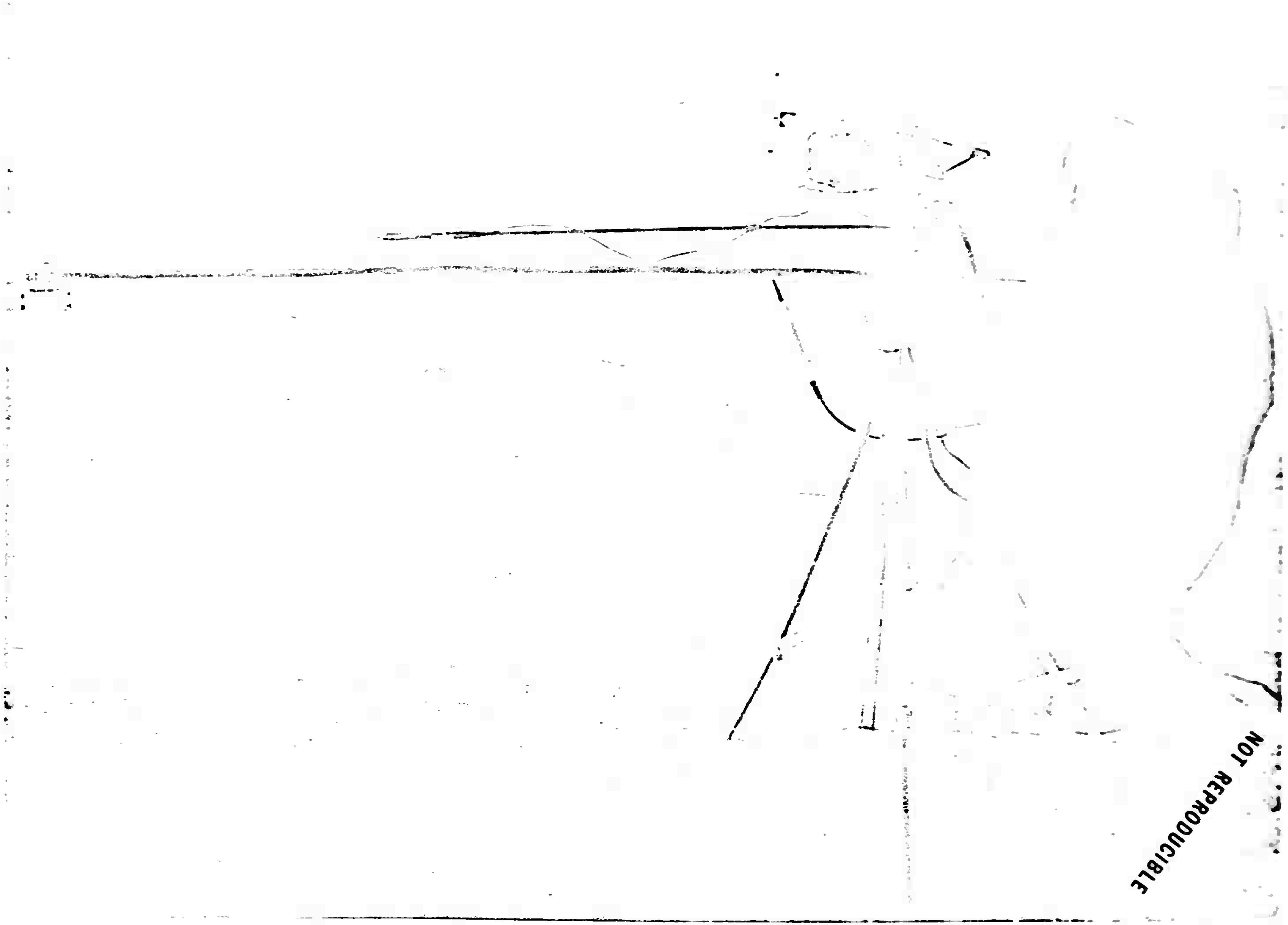
SUMMARY OF PRESENT AND PROPOSED STUDIES

STUDIES	STATUS
1. Surface measurements of radiation in the Arctic Basin to determine a radiation climatology by comparing data from different latitudes, locations, surfaces, etc.	
a) At T-3	Field work completed; computations and analysis in progress.
b) At Barrow	
c) At AIDJEX Sites	To be carried out in March/April 1972.
2. Airborne measurements to determine the effects of clouds and aerosols on radiative transfer in the Arctic atmosphere.	
a) Physical and radiative properties of Arctic stratus clouds (at Barrow).	Field work completed; analysis almost completed.
b) Aerosols (including ice crystal haze) in the Arctic atmosphere (at Barrow).	To be carried out at Barrow in March/April 1972.
c) Cloud and sea ice albedo measurements from aircraft (at AIDJEX Sites).	To be carried out at the AIDJEX Sites in spring 1972.
3. Mathematical modeling of radiative transfer in the Arctic atmosphere	In initial stages. Not originally proposed, but becoming increasingly important and now possible for us through access to NCAR computer.

PRELIMINARY RESULTS

1. Surface Measurements in the Arctic Basin at T-3, Barrow and at AIDJEX Sites

Radiation fluxes of short-wave incoming (global), short-wave reflected and net all-wave radiation were measured continuously through summer at both Barrow (27 May - 5 September) and T-3 (22 April - 29 October). Eppley precision pyranometers and Fritschen net radiometers were used. Fig. 1 shows the installation of the equipment at T-3 in April 1971. A PD-1 hemispherical all-wave sensor can be seen mounted on the tripod in the foreground of the photo. This instrument was used on occasions to obtain the outgoing all-wave radiative flux. Icing was severe on occasions, more so at T-3 than at Barrow, and frequent cleaning of the instruments and correction of the records was necessary. Table 1 shows a typical computer printout of data for both stations. Monthly summaries of total daily integrated radiation values will also be listed in the final tabulations. Fig. 2 shows a plot of typical values of global and net radiation when skies were clear at both stations. This occurred during the summer solstice on 21 June 1971 when Barrow (latitude 71° N) and T-3 (latitude 85° N) were approximately 2000 km apart. The effect of latitude on the diurnal variations of the radiative components is clearly recognizable. These basic measurements are useful in synthesizing a radiation climatology of the Arctic Basin, particularly if carried out over longer time spans. We have proposed to continue these studies in future years and to increase the density of the network during certain periods of observation and provide improved instrumentation in the form of additional short-wave and long-wave precision pyranometers. The PD-4 component radiometers which we proposed to use initially, are no longer being manufactured. All observing stations will eventually be equipped with instruments allowing the separation of the radiation balance into the four basic radiation components of incoming



NOT REPRODUCIBLE

Fig. 1 Installation of radiation equipment at T-3 in April 1971.

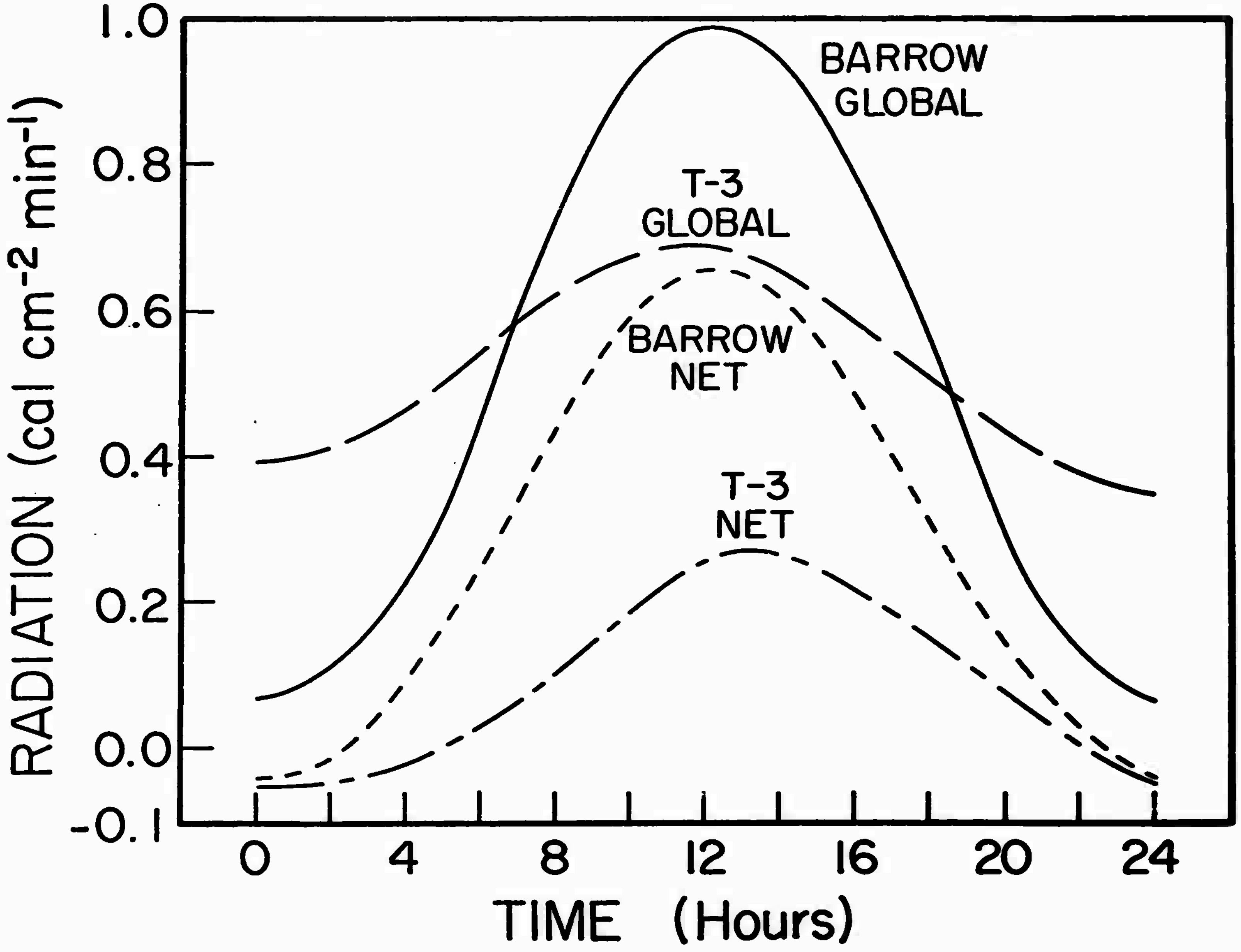


Fig. 2 Global and net radiation at Barrow and T-3 on 21 June 1971, with clear skies at both stations.

T-3 RADIATION DATA
CAL/(CM^2 MIN)

BARROW RADIATION DATA
CAL/(CM^2 MIN)

DATE= 5/31/71

TIME	SHORT IN	SHORT OUT	SHORT NET	ALBEDO	ALL NET	LONG NET	SHORT IN	SHORT OUT	SHORT NET	ALBEDO	ALL NET	LONG NET
000	0.42	0.40	0.02	0.94	-0.01	-0.03	0.04	0.04	0.0	[illegible]	[illegible]	[illegible]
100	0.46	0.42	0.03	0.93	0.01	-0.03	0.04	0.04	0.0	[illegible]	[illegible]	[illegible]
200	0.50	0.44	0.06	0.88	0.02	-0.04	0.03	0.03	0.0	[illegible]	[illegible]	[illegible]
300	0.55	0.46	0.08	0.85	0.03	-0.05	0.05	0.05	0.0	[illegible]	[illegible]	[illegible]
400	0.59	0.48	0.09	0.81	0.05	-0.04	0.12	0.11	[illegible]	[illegible]	[illegible]	0.0
500	0.62	0.50	0.12	0.80	0.06	-0.06	0.25	0.21	[illegible]	[illegible]	[illegible]	[illegible]
600	0.64	0.51	0.13	0.80	0.08	-0.05	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
700	0.66	0.53	0.13	0.80	0.08	-0.05	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
800	0.66	0.54	0.13	0.81	0.10	-0.03	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
900	0.68	0.54	0.13	0.80	0.11	-0.02	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1000	0.66	0.54	0.12	0.81	0.10	-0.02	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1100	0.64	0.51	0.13	0.80	0.10	-0.03	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1200	0.60	0.50	0.10	0.83	0.09	-0.01	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1300	0.57	0.47	0.09	0.83	0.07	-0.01	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1400	0.53	0.45	0.08	0.84	0.05	-0.03	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1500	0.49	0.43	0.06	0.88	0.04	-0.02	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1600	0.45	0.40	0.04	0.90	0.03	-0.02	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1700	0.42	0.38	0.03	0.92	-0.01	-0.04	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1800	0.39	0.37	0.02	0.95	-0.02	-0.04	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1900	0.37	0.35	0.02	0.96	-0.02	-0.04	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2000	0.36	0.35	0.01	0.97	-0.04	-0.05	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2100	0.34	0.34	0.02	0.95	-0.03	-0.05	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2200	0.37	0.36	0.01	0.99	-0.03	-0.04	[illegible]	0.11	[illegible]	[illegible]	[illegible]	[illegible]
2300	0.39	0.38	0.01	0.99	-0.03	-0.03	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

	CAL/(CM^2 DAY)				CAL/(CM^2 DAY)		CAL/(CM^2 DAY)				CAL/(CM^2 DAY)	
	SUM	SUM	SUM	MEAN	SUM	SUM	SUM	SUM	SUM	MEAN	SUM	SUM
	741.6	660.4	101.2	0.88	50.0	-51.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

EXPLANATIONS
SHORT IN= SHORT WAVE RADIATION INCOMING
SHORT OUT=SHORT WAVE RADIATION OUTGOING
SHORT NET=NET SHORT WAVE RADIATION
ALBEDO= SHORT OUT/SHORT IN
ALL NET= NET LONG AND SHORT WAVE RADIATION
LONG NET= NET LONG WAVE RADIATION

TABLE 1

SAMPLE LISTING OF RADIATION DATA FOR BARROW AND T-3, 31 MAY 1971

and outgoing short-wave and long-wave radiation. With an array of stations, the dynamic nature of the interaction between cloud advection and formation and the radiation balance can be studied. Such a high-density array will eventually be provided by the full-scale AIDJEX station grid. During spring 1972 we propose to study these processes on a macro-scale, by simultaneously observing the components of the radiation balance at Barrow, T-3 and the AIDJEX camp, during the AIDJEX pilot study.

The second set of surface measurements during Spring 1972 will be to extend the single-point observations at the stations listed above, to a greater spatial treatment of surface inhomogeneities. These inhomogeneities are present in the form of different types of ice, snow cover, ice-free and refrozen leads of various thickness, melt-ponds, hummocks and ice ridges. Spatial sampling of these types of surface will include measurements of albedoes and radiative surface temperatures. A study by Maykut and Untersteiner (1969) has shown how even small differences in albedo can be critical in considerations of the stability of a sea ice cover. Radiative surface temperatures were measured during April 1971 on a re-freezing lead close to T-3 (Fig. 3) and will be continued at the AIDJEX camp in the spring of 1972, when their immediate use as ground-truth for the planned NASA remote sensing overflights will be greatest. We also propose to continue these measurements at Barrow and T-3 whenever possible. The basic instrumentation used for this purpose is a PRT-5 infrared thermometer and a portable CSIRO albedometer. Airborne measurements of albedoes are described in Section 2c.

2. Airborne Measurements to Determine the Effects of Clouds and Aerosols on Radiative Transfer in the Arctic Atmosphere

a) Physical and radiative properties of Arctic stratus clouds

The Arctic radiation regime is dominated by low stratus cloud decks

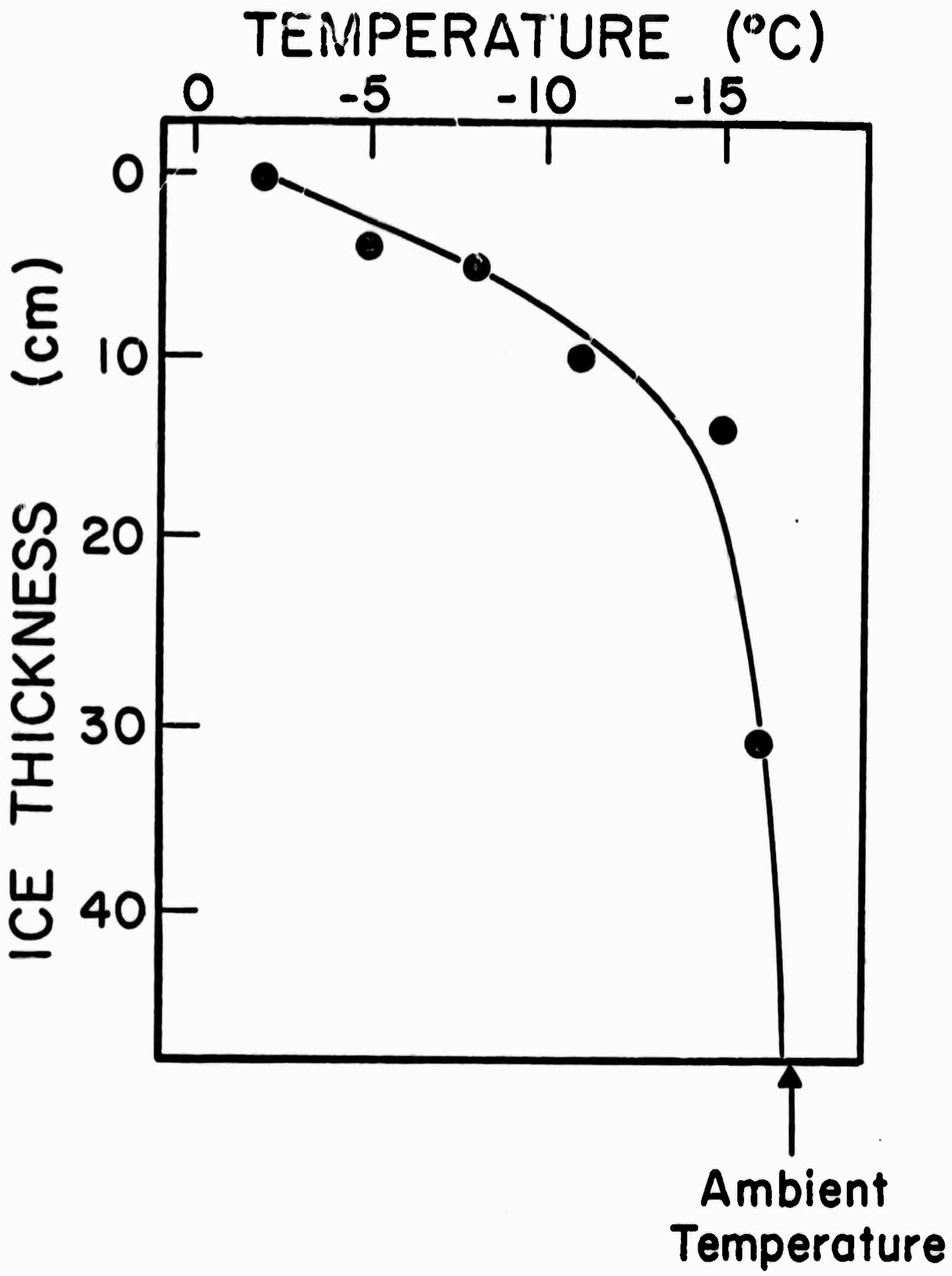


Fig. 3 Radiative surface temperatures of a re-freezing lead at T-3, April 1971.

during the summer, which have a considerable effect on the radiation balance of the surface and the atmosphere (Fletcher, 1965). Our efforts to define the role of stratus clouds in the Arctic atmosphere so far have concentrated on determining the physical and optical properties of these clouds, through a series of measurements with aircraft-mounted sensors. These flights took place at Barrow with light aircraft during August and September 1971, flying through multi-layered clouds decks up to altitudes of 4,000 meters.

Cloud particles were collected continuously with an MRI cloud particle sampler, seen mounted on a Cessna 180 aircraft in Fig. 4. Ice crystal densities were found to be of the order of 0.1 per litre at -10°C and less than 10^{-2} per litre at -7°C, i.e., close to expected ice nuclei concentrations. This small number will have a negligible effect on the radiative transfer in the clouds. The water drop spectrum did not vary appreciably from day to day in the stratus cloud. Some of these droplets are shown, magnified, in Fig. 5. A slight shift (up to 5 μ diameter in the mode) was observed for stratocumulus. The average size distribution for all days (counting approximately 4800 drops) is given in Fig. 6 which shows a mode of approximately 20 μ diameter. The number concentration varied from $50/cm^3$ for stratus to about $80/cm^3$ for stratocumulus giving a liquid water content of 0.2 to 0.4 gm/m^3. We propose to continue these studies, under:

1) non-precipitation conditions at lower temperatures, to determine the relationship between ice crystal concentrations and ice nuclei concentrations.
2) conditions of precipitation on the ground, to study the development and distribution of snow crystals at different heights.

Ice and condensation nuclei will be measured simultaneously on the ground, during aircraft sampling flights. These data will provide input parameters for our modeling effort, discussed in Section 3. Some of these

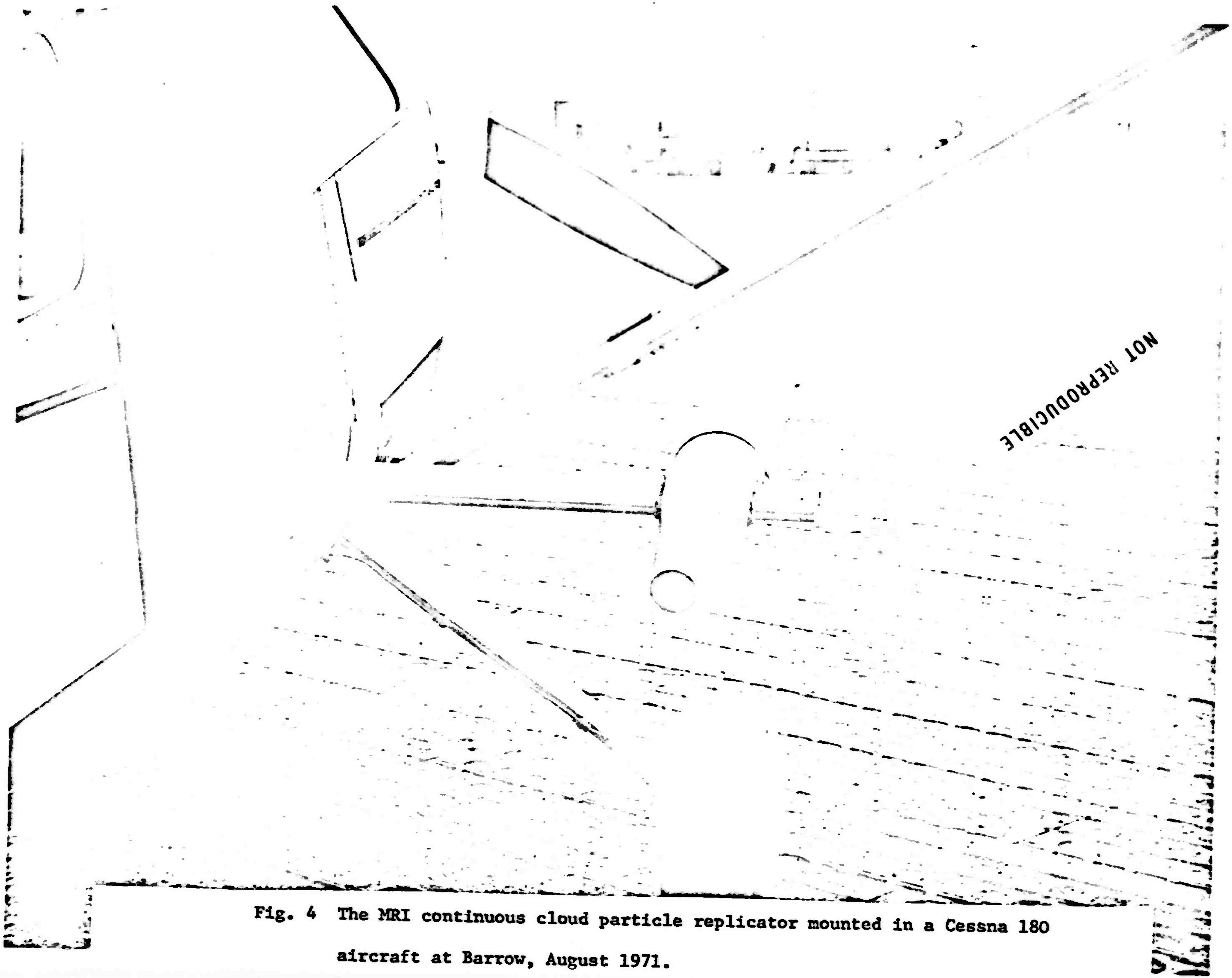


Fig. 4 The MRI continuous cloud particle replicator mounted in a Cessna 180 aircraft at Barrow, August 1971.

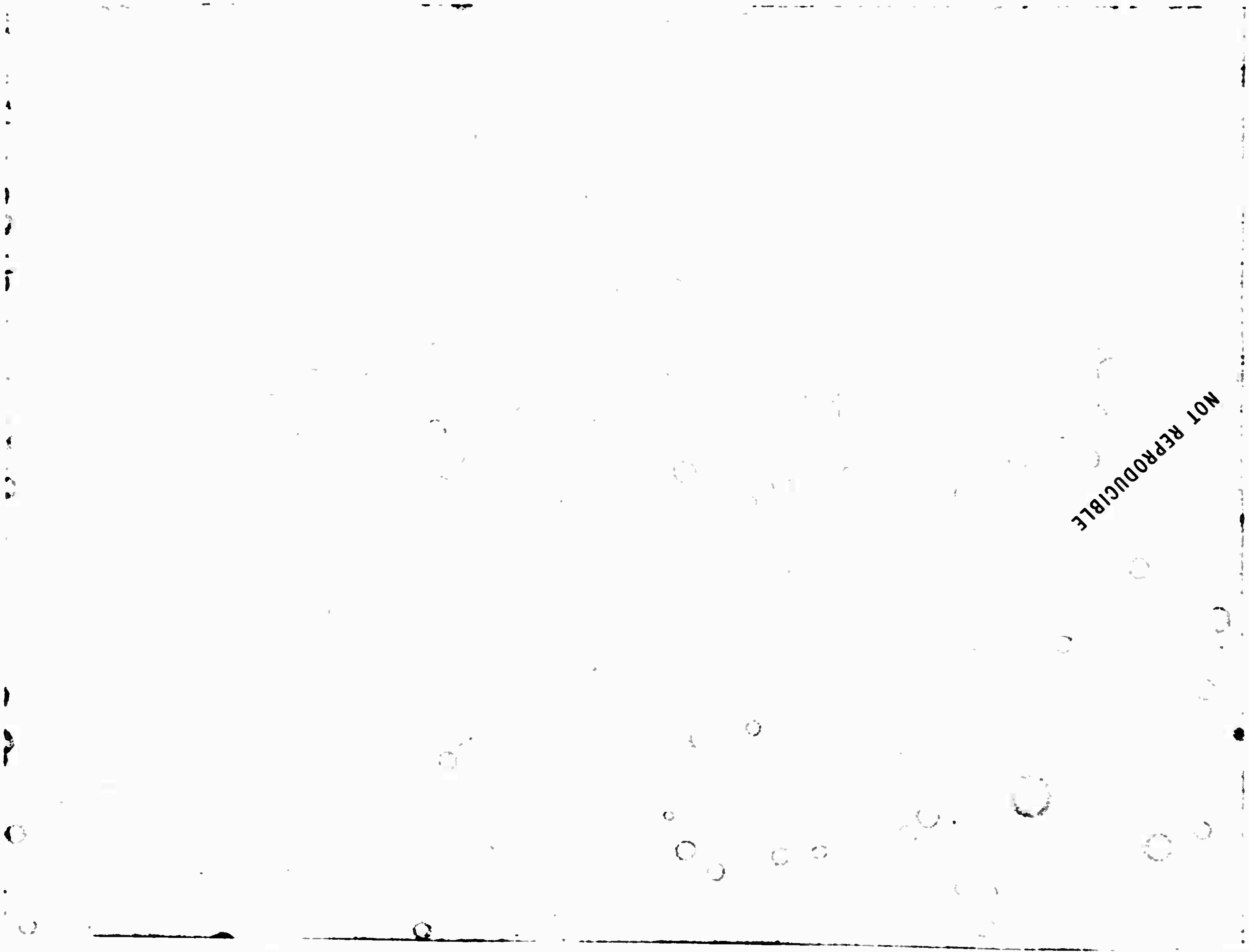


Fig. 5 Cloud droplet replicas, collected with the MRI sampler.

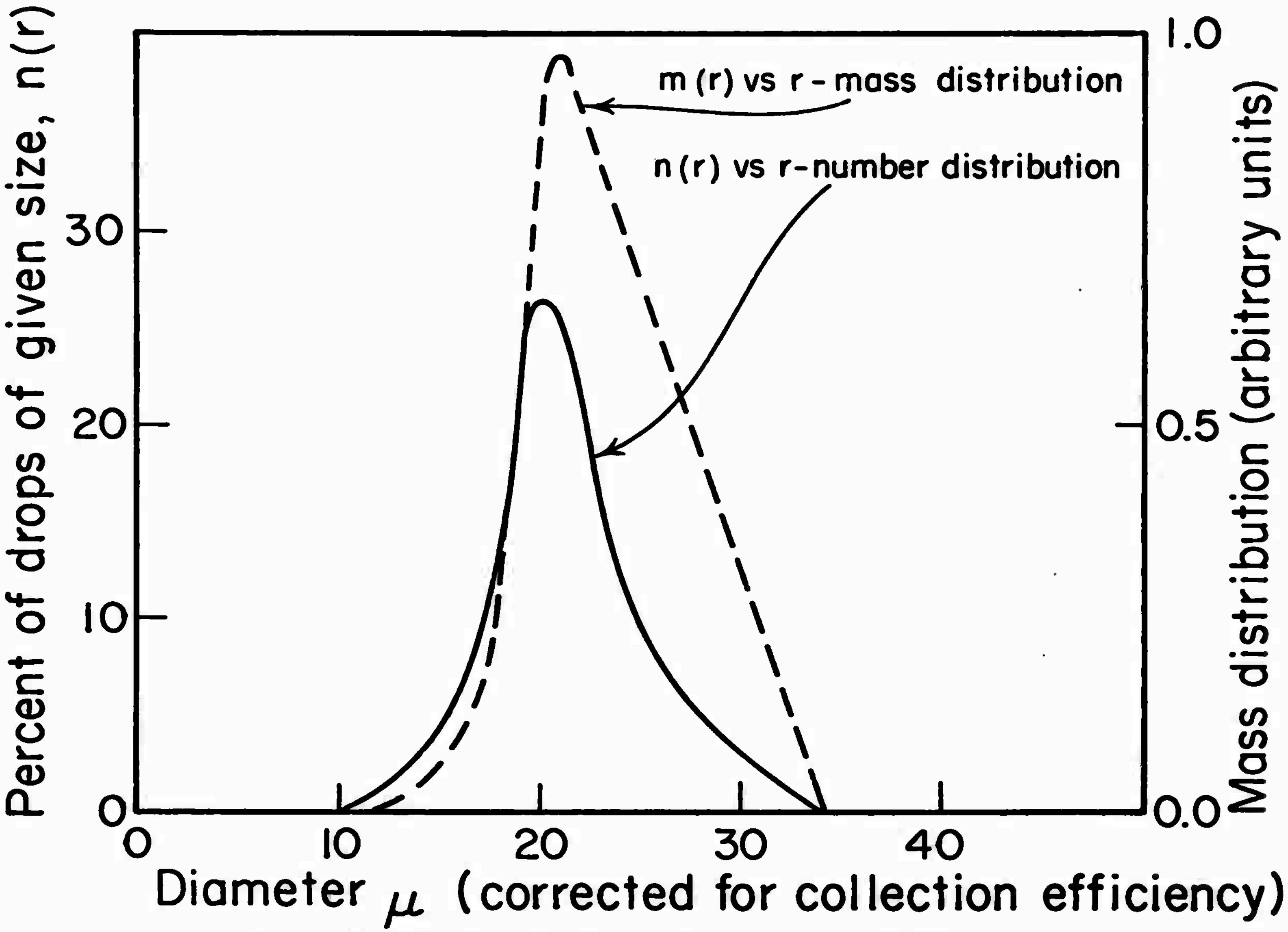


Fig. 6 Mass and number distribution of Arctic stratus cloud droplets at Barrow.

investigations will be commenced during spring 1972, but more systematic investigations will have to await continuation during 1972/73. A proposal to do this work has been submitted.

Cloud albedo measurements were carried out at the same time as the cloud sampling flights, using a light-weight CSIRO albedometer, mounted forward of the wing and attached to the strut of a Cessna 180. Fig. 7 shows typical results, indicating the wide spectrum of values obtained when the cloud cover is thin. Aircraft flying altitudes were 200 meters above the cloud, so that fifty percent of the sensor response comes from a cloud surface area 400 meters in diameter. This is a small area in terms of resolution elements of meteorological satellites, so that spatial variations of cloud albedoes due to holes will probably not be seen, except in the mean values. On the other hand, satellites such as the proposed ERTS-series will have several resolution elements covering the 400 meter diameter area, and will thus see the holes.

b) Aerosols in the Arctic atmosphere

A high background level of aerosols has been demonstrated to exist even in the Arctic atmosphere (Porch et al., 1970). These atmospheric aerosols, by virtue of their size, strongly diffract light in the visible region to give rise to a scattered, or diffuse, radiation field. In addition aerosols may also, depending upon their composition, selectively absorb radiation at certain wavelengths. The result of the interaction of incoming solar radiation with the particulate material in the air is to reduce the intensity of the solar radiation.

One can, provided that certain assumptions are met, describe the attenuation of incoming solar radiation as the combined results of scattering by air molecules, absorption by gases such as carbon dioxide and water vapor, and scattering and absorption by particulate material. If one considers

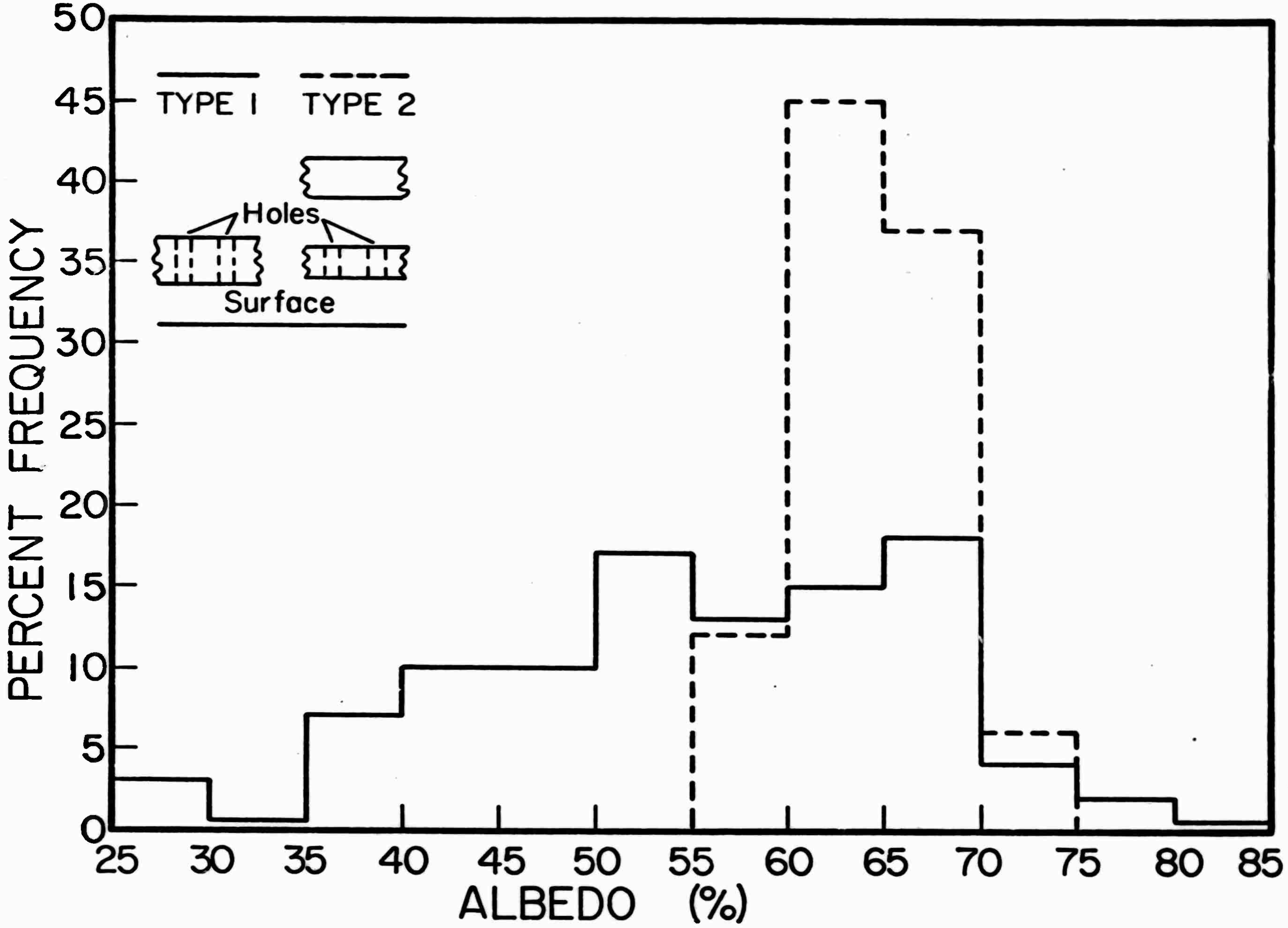


Fig. 7 Cloud albedo distribution for single and two-layered cloud deck at Barrow.

only those wavelengths where gaseous absorption is not present, then the attenuation results from the molecules and aerosols only. Since it is possible to accurately calculate the extinction arising from scattering by molecules (by employing the well-known Rayleigh scattering theory) one can, by making experimental observations of the solar attenuation, deduce the attenuating effects caused from aerosols alone. Thus, certain features of the atmospheric aerosols may be indirectly inferred by making measurements of the intensity of solar radiation at select wavelengths.

We will conduct experimental investigations of the height distribution of atmospheric aerosols over Arctic regions, by monitoring the intensity of the direct solar radiation in two narrow wavelength intervals (one at 0.4 microns and the other at 0.65 microns with effective bandwidths of about 0.01 micron) and at different levels in the atmosphere. The experimental apparatus will consist of a small photometer which is presently being constructed at the University of Alaska (Appendix I) and will be flown in a Cessna 180 aircraft out of Barrow, Alaska, in spring 1972. If these flights provide useful results, we would commence systematic investigations in our proposed continuation project.

The height distribution of the Mie volume attenuation coefficient, $\beta(\lambda,h)$, will be determined by applying the theory outlined in Appendix II. By inspecting the values of extinction coefficient at the two widely differing wavelengths it will be possible to determine information about the relative shape of the aerosol size distribution at each level. Furthermore, the information acquired on the height distribution of aerosol particles will be related to synoptic conditions or unusual source generation mechanisms such as diamond dust or blowing surface dust.

c) Cloud and sea ice albedo measurements from aircraft (at AIDJEX sites)

The albedo measurements of clouds commenced at Barrow during summer 1971

and described in section 2a will be continued at the AIDJEX sites during spring 1972. Also systematic albedo measurements of sea ice features will take place. Eppley precision pyranometers are presently being mounted in a Twin Otter aircraft which will fly routinely and frequently between the five data buoys surrounding the main camp at a radius of 400 kilometers. A vast amount of data on albedoes and also flux divergences should be obtained from these flights. Data recording will be on a strip-chart recorder.

3. Mathematical Modeling of Radiative Transfer in the Arctic Atmosphere

A synthesis of the various observational sub-programs is in the initial stages of progress. A systematic analysis can only be carried out after all data are available. This synthesis is now coupled with computer modeling, not originally proposed in this project, but made possible through our present access of a fast, cost-free computer. So far we have developed a computer model which will allow computation of infrared radiative fluxes and cooling rates below, in and above a single stratus cloud deck. This program is presently running on the CDC 6600/7600 computer of the National Center for Atmospheric Research at Boulder, where one of us (Dr. Sue Ann Bowling) works presently as visiting scientist. Mie scattering programs are available at NCAR and work will begin shortly on computation of optical coefficients appropriate for Arctic stratus cloud, taking the cloud data of section 2a as input. We have also begun work on diffuse transmission through multiple cloud decks, and development of this model is expected to be complete by the middle of this year. A sub-model of short-wave transmission through a haze layer is progressing satisfactorily in mathematical form, but programming has not yet commenced.

We propose to carry on this work as follows: 1) Go through any data collected on temperature soundings, cloud heights, depths, and densities, presence, density, and particle size of ice crystal hazes, water clouds,

etc., and reduce this data to the proper form to fit the computer model(s); 2) Compute the net long-wave and possibly short-wave fluxes under various conditions; 3) Compare the results with observed radiometer data; and 4) If the model results appear reasonable, use the model to predict the effect on the radiation balance of perturbation in such parameters as cloudiness, area of puddling, surface temperature of puddles, presence or absence of contrail cirrus, cloud height and temperature, open water and associated sea smoke, etc. The model could also pick up variations in atmospheric energy loss due to changes in these parameters.

The NCAR computer is available without charge to UCAR member universities, of which we are one. We propose to continue using these computer facilities, since, for example, the multiple cloud deck program probably would require excessive computation times on the University of Alaska's IBM 360-40 computer, requiring repeated (441 times) inversions of a 14 x 14 matrix.

APPENDIX I

Instrumentation for Aerosol Measurements

The portable photometer, presently being constructed, will consist of a battery-operated device which will be manually pointed at the sun by an observer. The instrument's field of view will be large enough so that human pointing accuracy in a somewhat unstable small aircraft will be sufficient to keep the solar disk within the angular cone of the radiometer. Calculations indicate that the amount of diffuse sky radiation contained within a circular field of view with a diameter of 5 degrees is entirely negligible with respect to the direct solar radiation, provided that the measurements are taken for solar elevation angles greater than 30 degrees and that the skies are clear (as they are expected to be over Barrow when measurements are taken). By using a Fabrey optical imagery scheme, it will be possible to design the optical response to be constant within about 10 percent over the entire 5 degree angular cone. For normal flying conditions over Barrow it will be possible to keep the solar disk within this field by merely sighting the disk through a telescope with appropriate neutral density filters.

The wavelength intervals will be defined by passing the direct solar radiation through narrow band interference filters having total transmissions at center wavelength of about 30 percent and less than 0.1 percent total transmission outside of bandpass regions. The photodetector will be a PIN doped solid state silicon device which will feed into integrated circuitry amplifiers and, eventually, to a chart recorder. Duplexing between the two channels will proceed with a time constant of 5 seconds with appropriate integration.

Ancillary information such as ambient air temperature, altitude and local mean time will be sampled occasionally, either by noting the values on the chart recorder or by occasionally entering them verbally into a

tape recorder.

APPENDIX II

Theory of Aerosol Scattering

The attenuation of incoming solar radiation, provided that certain physical assumptions are met, can be quantitatively described through the Beer-Lambert law which may be written as,

$$1)\quad I(\lambda,z,h) = I_o(\lambda)\ \mathrm{EXP} - [\tau_{OR}\ (\lambda)\ \frac{P(h)}{P_o} + \tau_{ABS}(\lambda) + \int_h^\infty \beta_D(h,\lambda)\ dh]\ m(z)$$

where,

λ = wavelength of incoming direct solar radiation (u)

z = solar zenith angle

h = height above mean sea level

$I\ (\lambda,z,h)$ = observed solar intensity at h and z

$I_o\ (\lambda)$ = magnitude of incoming direct solar radiation

τ_{OR} = optical depth at mean sea level due to Rayleigh scattering

$P\ (h)$ = atmospheric pressure at height h

P_o = atmospheric pressure at mean sea level

$\tau_{ABS}(\lambda)$ = optical depth arising from gaseous absorbtion

$\beta_D(h,\lambda)$ = volume extinction coefficient for aerosols at h and λ

$m(z) = \dfrac{\tau\ \text{slant}\ (\lambda,h)}{\tau\ \text{vertical}\ (\lambda,h)} \cong \sec\ (z)$ = relative airmass

The height derivitive of Eqn. 1 is given by

$$2)\quad \frac{dI\ (\lambda,z,h)}{dh} = -I\ (\lambda,z,h) \cdot \sec\ (z)\ \{\frac{\tau_{OR}}{P_o}\frac{dP(h)}{dh} + {}_D\ (h,\lambda)\}$$

where,

$$\frac{dP(h)}{P_o dh} \cong -\frac{1}{H}\, e^{\frac{-h}{H}},\ H \simeq 8\ \text{km}$$

In Eqn. 2 the term having to do with absorption by gases was not included

since it is assumed that observations will be made in wavelength intervals taken outside of the absorbtion features.

From Eqn. 2, the extinction coefficient arising from Aerosols alone, $\beta(h,z)$, is given by,

$$3)\quad \beta_D(h,\lambda) = -\frac{1}{\sec(z)} \cdot \frac{d\ \ln I\ (\lambda,z,h)}{dh} + \frac{\tau_{OR}\, e^{-\frac{h}{H}}}{H}$$

Thus by noting the value of the logarithmic derivitive of observed solar radiation one can determine the value of the volume extinction coefficient, $\beta_D(h,\lambda)$, at each height.

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